Pay attention to your manipulation checks! Reward impact on cardiac reactivity is moderated by task context

Richter, Michael

How to cite

RICHTER, Michael. Pay attention to your manipulation checks! Reward impact on cardiac reactivity is moderated by task context. In: Biological psychology, 2010, vol. 84, n° 2, p. 279–289. doi: 10.1016/j.biopsycho.2010.02.014

This publication URL: https://archive-ouverte.unige.ch/unige:10680

Publication DOI: 10.1016/j.biopsycho.2010.02.014

Running head: MANIPULATION CHECKS AND CARDIAC REACTIVITY

Pay Attention to Your Manipulation Checks! Reward Impact on Cardiac Reactivity is Moderated by Task Context.

Michael Richter

University of Geneva, Switzerland

Keywords: reward, task context, cardiovascular reactivity

Correspondence should be sent to:
Michael Richter
Department of Psychology
University of Geneva
40, Bd. du Pont-d'Arve
CH-1211 Geneva 4
Switzerland
Phone: +41 22 379 92 32
Fax: +41 22 379 92 19
E-mail: Michael.Richter@unige.ch

Abstract

Two experiments assessed the moderating impact of task context on the relationship between reward and cardiovascular response. Randomly assigned to the cells of a 2 (task context: reward vs. demand) x 2 (reward value: low vs. high) between-persons design, participants performed either a memory task with an unclear performance standard (Experiment 1) or a visual scanning task with an unfixed performance standard (Experiment 2). Before performing the task—where participants could earn either a low or a high reward—participants responded to questions about either task reward or task demand. In accordance with the theoretical predictions derived from Wright's (1996) integrative model, reactivity of pre-ejection period increased with reward value if participants had rated aspects of task reward before performing the task. If they had rated task demand, pre-ejection period did not differ as a function of reward.

Pay Attention to Your Manipulation Checks! Reward Impact on Cardiac Reactivity is Moderated by Task Context.

Common sense suggests that the more you desire something the harder you will work to get it. In cardiovascular psychophysiology this idea is reflected by the hypothesis that cardiovascular responses are a direct function of reward value: the more valuable a reward, the higher the cardiovascular response (e.g., Belanger & Feldman, 1962; Brenner, Beauchaine, & Sylvers, 2005; Elliot, 1969; Fowles, 1983; Fowles, Fisher, & Tranel, 1982; Lipsitt, Reilly, Butcher, & Greenwood, 1976; Tranel, 1983; Tranel, Fisher, & Fowles, 1982; Smith, Allred, Morrison, & Carlson, 1989; Smith, Nealey, Kircher, & Limon, 1997; Smith, Ruiz, & Uchino, 2000). Drawing on an analysis by Wright (1996), Richter and Gendolla (2006, 2007, 2009) specified the conditions under which cardiovascular responses in active coping situations should be a function of reward value. They demonstrated that the proportional relationship between reward value and cardiovascular response only holds if individuals perform a task with an *unclear* performance standard. If individuals perform a task with a *clear* performance standard, reward and cardiovascular responses bear no direct relation. These results seem to suggest that the clarity of the performance standard determines the impact of reward on cardiovascular responses. The present research aims to broaden this perspective by demonstrating that the performance standard is not crucial but that the general task context moderates the reward-cardiovascular response relationship.

Motivational Intensity Theory and Active Coping

Integrating motivational intensity theory (Brehm & Self, 1989) and the active coping approach (Obrist, 1981), Wright (1996) developed a model that predicts cardiovascular responses in active coping situations. Motivational intensity theory is concerned with the mobilization of resources for the execution of instrumental behavior. According to the theory, resource mobilization is governed by a conservation principle. Trying to avoid wasting resources, individuals invest only the resources that are necessary for task success. Since task difficulty indicates the amount of necessary resources, resource investment should rise with increasing task difficulty. This proportional relationship between task difficulty and resource mobilization is limited by two variables: task difficulty and success importance. (1) If task difficulty is so high that success is impossible, individuals should withhold resources. (2) If the necessary resources for task success outweigh the benefits, individuals should disengage, as well. In sum, resource mobilization should depend on task difficulty as long as task success is possible and the necessary resources are justified by success importance. However, this hypothesis should only be valid for instrumental tasks with a clear and fixed performance standard. In contrast, if the performance standard (i.e., task difficulty) is either unclear or can be chosen by the performers themselves, resource mobilization should directly increase with success importance—which depends on needs, task instrumentality, and reward value.[1]

Wright (1996) integrated these predictions of motivational intensity theory (Brehm & Self, 1989) with Obrist's observation that task engagement in active coping tasks (i.e., when task outcome depends on the performer's performance) is associated with (sympathetic) beta-adrenergic impact on the heart (e.g., Light & Obrist, 1980; Obrist, 1976; Obrist et al., 1978; Obrist, Light, James, & Strogatz, 1987). Drawing on both approaches, Wright predicted that cardiovascular reactivity—the change in cardiovascular activity from rest to task performance—should rise with task difficulty as long as the necessary resources are justified and task success is possible. If the performance standard is unknown, cardiovascular reactivity should be a direct function of success importance. He further specified that among the cardiovascular parameters systolic blood pressure (SBP), diastolic blood pressure (DBP), and heart rate (HR), SBP should be the most sensitive to variations in resource investment or task engagement, respectively. SBP is a function of both the force of myocardial contraction and the total peripheral resistance. Correspondingly, it reflects beta-adrenergic activity—which is the main determinant of myocardial contraction force (Berne & Levy, 1977; Ganong, 2005)—when the effects of total peripheral resistance are negligible. Since total peripheral resistance has a strong influence on DBP, effects of myocardial contraction force on DBP are more likely to be masked by effects of total peripheral resistance than effects on SBP. HR is a function of both sympathetic and parasympathetic effects and only reflects sympathetic changes if parasympathetic activity does not change.

In the last ten years evidence supporting Wright's approach has accumulated (Gendolla & Wright, 2005; Richter, Gendolla, & Krüsken, 2006; Wright & Kirby, 2001, for reviews). Various empirical studies have demonstrated that cardiovascular reactivity—especially SBP reactivity—in active coping situations is a joint function of task difficulty and success importance if performance standards are fixed and clear (e.g., Eubanks, Wright, & Williams, 2002; Gendolla & Richter, 2006; Wright, Dill, Russell, & Anderson, 1998). Researchers have also begun to investigate the underlying physiological mechanisms in more detail by assessing pre-ejection period (PEP) (Annis, Wright, & Williams, 2001; Richter, Friedrich, & Gendolla, 2008; Richter & Gendolla, 2009). PEP is the time interval between the onset of ventricular depolarization and the opening of the aortic valve. It constitutes one of the best non-invasive indicators of beta-adrenergic impact on the heart (Sherwood et al., 1990) and enables a more valid test of whether myocardial beta-adrenergic activity plays the predicted role in resource mobilization.

There is also support for the hypothesis that success importance directly determines cardiovascular reactivity when individuals have no clear idea about the performance standard of a task (Richter et al., 2006; Richter & Gendolla, 2007, 2009) or when they are free to choose their own performance standard (Wright, Killebrew, & Pimpalapure, 2002; Wright, Tunstall, Williams, Goodwin, & Harmon- Jones, 1995). Participants in a study by Richter et al. (2006) worked on either an easy (Experiment 1) or an impossible (Experiment 2) memory task. In both experiments participants could earn either a low or a high reward by successfully performing the task. All participants were informed about the general task procedure but only one half received additional information about the difficulty of the task. The other half received no task difficulty information. In both experiments, cardiovascular reactivity was higher in the high reward condition than in the low reward condition if participants were not informed in advance about the difficulty of the task. If participants received task difficulty information before performing the task, reward value and cardiovascular reactivity were dissociated.

The results reviewed above seem to suggest that the clarity of the performance standard determines if reward value and cardiovascular response are associated in active coping tasks. However, these effects might also reflect a more general principle. Informing participants that they can earn a reward by successfully performing a task renders task reward salient. Providing additional information about task difficulty heightens the salience of task demand. According to motivational intensity theory, resource mobilization should be governed by task difficulty if task demand is salient, whereas task reward should determine resource mobilization if task demand is unknown (i.e., not salient). Correspondingly, the impact of reward on cardiovascular reactivity should vary with the task context. (1) If the task context renders task reward salient, cardiovascular reactivity should increase with increasing reward value. (2) If task demand is salient in a given context, reward value should have no direct impact on cardiovascular reactivity.

The aim of the presented research was to demonstrate that the impact of reward on cardiovascular responses is moderated by the task context. Specifically, I tried to demonstrate that ”manipulation checks” presented before task performance can modify the impact of reward on cardiovascular reactivity. If participants respond to questions about task reward, task reward should be salient and reward value should directly determine cardiovascular reactivity (i.e., high cardiovascular reactivity under conditions of high reward, low cardiovascular reactivity under conditions of low reward). If they answer questions about task demand, task difficulty should be salient and reward value should have no impact on cardiovascular reactivity. Based on previous research and Obrist’s hypothesis about the association between task engagement and beta-adrenergic impact, I expected the joint effect of task context and reward to be especially pronounced for PEP reactivity.

Experiment 1

Method

Participants and Design

Fifty-one psychology students (mean age 24 years) participated for course credit. They were randomly assigned to the cells of a 2 (task context: reward vs. demand) x 2 (reward: 2 Swiss Francs vs. 12 Swiss Francs) between-persons design. The distribution of women and men was as follows: 13 women and 1 man in the demand-2-Swiss-Francs cell, 12 women and 2 men in the demand-12-Swiss-Francs cell, 12 women and 1 man in the reward-2-Swiss-Francs cell, and 10 women in the reward-12-Swiss-Francs cell. Participation was anonymous and voluntary. Given the low number of men, I will only report the results for the sample restricted to female participants. The results for the unrestricted sample were virtually identical.

Apparatus and Physiological Measurement

A Vasotrac APM 205A system (Medwave, Arden Hills, MN) and a Cardioscreen 1000 system (medis, Ilmenau, Germany) assessed cardiovascular measures during baseline period and task performance. The Vasotrac system measured SBP, MAP, and DBP (all in millimeters of mercury [mmHg]) with a cuff placed around the wrist of the participant's non-dominant arm. One blood pressure measure was obtained every 12 to 15 heart beats. The Cardioscreen system used four pairs of disposable spot electrodes to assess an electrocardiogram (ECG) and thoracic impedance (impedance cardiogram, ICG) (see Scherhag, Kaden, Kentschke, Sueselbeck, & Borggrefe, 2005, for a validation of the system). Sampling rate was 800 Hz. The spot electrodes were placed on the right and left side of the base of the participant's neck and on the left and right middle axillary line at the height of the xiphoid. Both systems directly stored the collected measures on a computer disk so that participants and experimenter were ignorant of all values assessed during the experiment. The experimenter was hired and ignorant of the hypotheses. Experiment generation software (INQUISIT by Millisecond Software, Seattle, WA) controlled the presentation of the stimuli and instructions and collected participants' responses.

Procedure

The experiment was run in individual sessions. After the participant had signed informed consent, the experimenter assessed participant's weight and height and applied the blood pressure cuff and the spot electrodes. The participants then answered some biographical questions. During the following baseline period, participants could leaf through a magazine. Cardiovascular measures were continuously assessed during the baseline period. After 10 minutes the cardiovascular measures were stopped and the participants received task instructions.

I administered a memory task that has been successfully employed in previous studies on cardiovascular reactivity under conditions of a fixed but unclear performance standard (Richter & Gendolla, 2006, 2007). The task consisted of a list of 10 random letter series each consisting of four letters. Total performance time was five minutes. The 10 letter series were not presented all at once but were sequentially added to the list in intervals of 30 seconds. Thus, at the beginning of task performance only the first letter series was presented on the screen. After 30 seconds the second letter series was added, after 60 seconds the third series appeared, and so on. Thirty seconds before the end of task performance, all ten letter series were visible. All participants learned that they would receive a reward if they could correctly recall all of the presented letter series after task performance. One half of the participants could win 2 Swiss Francs (about USD 1.8), the other half could win 12 Swiss Francs (about USD 10.8). Corresponding to the manipulations that have been previously employed to create tasks with a fixed but unclear performance standard (Richter & Gendolla, 2006, 2007, 2009), task instructions explained only the general procedure of the task. Participants did not receive concrete information concerning task difficulty. They were not informed about total task duration, the total number of letter series, the number of letters of each series, or the interval between the appearance of the different letter series.

After having read task instructions, participants answered five questions related either to task demand (*demand context*) or to task reward (*reward context*). In the demand condition participants rated the following questions: ”How much effort will be necessary to successfully perform the task?”, ”Will you be able to successfully perform the task?”, ”How exhausting will it be to successfully perform the task?”, ”How likely is it that you will successfully perform the task?”, ”How difficult will it be to successfully perform the task?”. In the reward condition participants answered the following questions: ”Will you be satisfied after having successfully performed the task?”, ”How important is it for you to successfully perform the task?”,”How valuable does the reward appear to you?”, ”How important is it for you to earn the promised reward?”, ”How attractive does the reward appear to you?”. All questions were rated on scales ranging from *not at all* (1) to *very much* (9). The order of presentation of the questions was randomized. After having responded to the five questions, participants performed the memory task for five minutes. Cardiovascular measures were continuously assessed during this time. After task performance, participants rated the difficulty of the task (”How difficult did task success appear to you?”) on a scale ranging from *not at all* (1) to *very much* (9). Finally, participants were debriefed, probed for suspicion, and received their course credit and the monetary reward if applicable.

Data Scoring, Reduction, and Analysis

The Cardioscreen system automatically downsampled the ECG and ICG signals to 200 Hz. A threshold peak-detection algorithm identified R-peaks, which were visually confirmed afterwards (ectopic beats were deleted, see Lippman, Stein, & Lerman, 1994). The first derivative of the change in thoracic impedance was calculated and the resulting dZ/dt-signal was ensemble averaged over periods of 60 seconds using the detected R-peaks (Kelsey & Guethlein, 1990). Only artifact-free cycles were used to construct the ensemble averages. Two independent raters visually inspected and, if necessary, corrected R-onset and B-point locations as recommended by Sherwood et al. (1990). PEP (in milliseconds [ms]) was computed as the interval between R-onset and B-point (Berntson, Lozano, Chen, & Cacioppo, 2004). Since the inter-rater agreement was high (ICC[2,1] = .92) (Shrout & Fleiss, 1979), the arithmetic mean of both raters' PEP values was used for the analyzes.

Given that some researchers have proposed measures of heart rate variability (HRV) to assess effort mobilization or resource investment, respectively (e.g., Mulder, Rusthoven, Kuperus, de Rivecourt, & de Waard, 2007; Segerstrom & Solberg Nes, 2007; Vicente, Thornton, & Moray, 1987), I computed and analyzed HRV measures for exploratory purposes. Based on the identified R-peaks and the corresponding inter-beat intervals (IBI), the root mean square of successive differences (RMSSD) was calculated as a time-domain HRV measure. As frequency-domain HRV measures, I computed low frequency HRV (LF-HRV; 0.04 Hz – 0.15 Hz) and high frequency HRV (HF-HRV; 0.15 Hz – 0.4 Hz) using the Kubios HRV analysis software (version 2.0, Biomedical Signal and Medical Imaging Analysis Group, Department of Applied Physics, University of Kuopio, Finland). The IBI series was interpolated at 4 Hz, detrended using the smoothness priors method (Tarvainen, Ranta-aho, & Karjalainen, 2001), and the low and high frequency spectra were calculated with Welch's periodogram method (window width was 256 seconds, window overlap was 50%). Finally, HRV spectra values and RMSSD were logarithmically (ln[x + 1]) transformed to deal with the skewedness of the data.

I computed cardiovascular baseline scores as the arithmetic means of all measures collected during the last five minutes of habituation (Cronbach's αs > .95). The arithmetic means of all measures obtained during task performance constituted our cardiovascular task scores (Cronbach's αs > .97). Cardiovascular reactivity scores were computed for each participant and each cardiovascular parameter by subtracting baseline scores from their respective task scores (Llabre, Spitzer, Saab, Ironson, & Schneiderman, 1991). Given that reactivity scores of IBI, RMSSD, LF-HRV, and HF-HRV significantly correlated with their respective baseline scores ($-.56 < r$s $< -.29$, ps $< .05$), baseline scores were included as covariate in all analyses involving these measures. SBP, DBP, and PEP reactivity scores did not significantly correlate with their baseline scores ($-.11 < r$s $< -.04$, ps $> .48$) and, correspondingly, their reactivity scores were not adjusted with regard to baseline values (Benjamin, 1967; Llabre et al., 1991).

Given that the specific theory-driven predictions about the joint impact of task context and reward value on beta-adrenergic reactivity lead to a pattern that is not adequately capture by the tests of a conventional 2 x 2 ANOVA, I analyzed all cardiovascular reactivity scores with a planned contrast (Furr & Rosenthal, 2003; Rosenthal & Rosnow, 1985). Contrast cell weights were as follows: -1 for the demand-2-Swiss-Francs cell, -1 for the demand-12-Swiss-Francs cell, -1 for the reward-2-Swiss-Francs cell, and +3 for the reward-12-Swiss-Francs cell. Following this main contrast, two further contrasts examined the impact of reward at each level of task context.

Results

Preliminary Analyses

Using participants' weight and height, Body-Mass-Indexes (BMI) were calculated. An analysis of BMI values with a 2 (task context: reward vs. demand) x 2 (reward value: 2 Swiss Francs vs. 12 Swiss Francs) between-persons ANOVA showed no significant effects (ps $> .22$). Furthermore, BMI values did not significantly correlate with any of the cardiovascular baseline or reactivity scores ($-.24 < r$s $< .13$, ps $> .11$).

Cardiovascular Baselines

There were no significant effects on cardiovascular baseline scores (*p*s > .16) in 2 (task context) x 2 (reward value) between-persons ANOVAs. Cell means and standard errors appear in Table 1.

Cardiovascular Reactivity

PEP reactivity. The planned contrast approached significance, *F*(1, 43) = 3.19, *p* = .08, *MSE* = 43.18, = .07, the residual was not significant (*p* = .36). Analyses of the impact of reward at each level of task context showed that PEP reactivity was significantly stronger in the reward-12-Swiss-Francs cell (*M* = -7.83, *SE* = 2.91) than in the reward-2-Swiss-Francs cell (*M* = -1.58, *SE* = 1.10), *F*(1, 43) = 4.94, *p* = .03, = .10, but did not differ between the demand-12-Swiss-Francs cell (*M* = -4.86, *SE* = 2.01) and the demand-2-Swiss-Francs cell (*M* = -4.51, *SE* = 1.61) (*p* = .90). Figure 1 displays the pattern of PEP reactivity.[2]

Blood pressure reactivity. The planned contrast was not significant for SBP, MAP, or DBP reactivity (*p*s > .43). Furthermore, there were no significant differences between the reward-2-Swiss-Francs and the reward-12-Swiss-Francs cells (*p*s > .72) or between the demand-2-Swiss-Francs and the demand-12-Swiss-Francs cells (*p*s > .79). Table 2 shows cell means and standard errors of SBP, MAP, and DBP reactivity.

IBI reactivity. The planned contrast was not significant (*p* = .99). The reward-2-Swiss-Francs and the reward-12-Swiss-Francs cells as well as the demand-2-Swiss-Francs and the demand-12-Swiss-Francs cells did not differ from one another (*p*s > .61). Table 2 displays cell means and standard errors of IBI reactivity.

HRV reactivity. The planned contrast was not significant for RMSSD (*p* = .10) and the reward cells did not differ within the task context conditions (*p*s > .49). The planned contrast was significant for LF-HRV, *F*(1, 41) = 7.65, *p* = .01, *MSE* = 0.34, = .16 (residual *p* = .14), and approached significance for HF-HRV, *F*(1, 41) = 3.95, *p* = .053, *MSE* = 0.31, = .09 (residual *p* = .35). No statistical significant differences between both reward groups within the task context conditions emerged (*p*s > .36) for HF-HRV reactivity. LF-HRV reactivity was significantly higher in the reward-12-Swiss-Francs cell than in the reward-2-Swiss Francs, $F(1, 41) = 6.04$, $p = .03$, = .13. The demand cells did not significantly differ from one another ($p = .36$). Table 2 displays cell means and standard errors of HRV reactivity.

Task Performance

A 2 (task context) x 2 (reward value) between-persons ANOVA did not reveal any significant effects on the number of correctly recalled letter series (*p*s > .36). Furthermore, Tukey's HSD tests did not show any significant differences between the four cells (*p*s > .67). The number of correctly recalled letter series did not significantly correlate with any of the cardiovascular reactivity scores (-.24 < *r*s < .23, *p*s > .12). Cell means and standard errors of the number of correctly recalled letter series were as follows: $M = 6.08$ and $SE = 0.80$ in the reward-2-Swiss-Francs cell, $M = 4.80$ and $SE = 0.57$ in the reward-12-Swiss-Francs cell, $M = 5.23$ and $SE = 0.83$ in the demand-2-Swiss-Francs cell, $M = 5.17$ and $SE = 0.64$ in the demand-12-Swiss-Francs cell.

Task Ratings

I compared the pre-task ratings within each task context condition using *t*-tests for independent samples. There were only two significant differences between the reward-2-Swiss-Francs cell and the reward-12-Swiss-Francs cell. Reflecting our manipulation of reward value, participants in the reward-12- Swiss-Francs cell rated the reward as more attractive and more valuable than

participants in the reward-2-Swiss-Francs cell (*t*[20]s > 3.47, *p*s < .003). All other comparisons were not significant (*p*s > .22). Table 3 shows the cell means and the standard errors of the pre-task ratings. A 2 (task context) x 2 (reward value) between-persons ANOVA of the post-task difficulty ratings did not reveal any significant effect (*p*s > .14). Cell means and standard errors of the post-task difficulty ratings were as follows: $M = 7.58$ and $SE = 0.45$ in the reward-2-Swiss-Francs cell, $M = 6.20$ and $SE = 0.81$ in the reward-12-Swiss-Francs cell, $M = 6.86$ and $SE = 0.49$ in the demand-2-Swiss-Francs cell, $M = 6.50$ and $SE = 0.57$ in the demand-12-Swiss-Francs cell.

Discussion

The observed PEP reactivity pattern supports the predicted moderating impact of task context on the relationship between reward value and cardiovascular reactivity. Even if the main contrast did not attain the conventional level of significance, analyses of the impact of reward at each level of task context demonstrated that the PEP reactivity pattern emerged as predicted. If participants had rated aspects of the monetary reward before performing the task, PEP reactivity increased with increasing reward value: PEP reactivity was high when participants could earn 12 Swiss Francs and was low when they could earn only 2 Swiss Francs. If participants had rated task demand before task performance, PEP reactivity did not significantly differ as a function of reward value.

This pattern was also statistically significant for LF-HRV reactivity and approached significance for HF-HRV reactivity: If participants had rated task reward before task performance, HRV reactivity was higher when participants could win the higher reward. If participants had rated task demand, HRV reactivity did not differ as a function of reward value. However, even if the LF-HRV pattern was statistically significant, it should be noted that the observed pattern is inconsistent with preceding research that has advocated frequency domain measures as measures of mental effort. For instance, Mulder and colleagues (2007) suggested that LF-HRV decreases with increases in mental effort. Consequently, one would expect that LF-HRV reactivity is more negative when participants engage to earn the high reward than when they try to earn the low reward. In the present study, LF-HRV reactivity showed the inverted pattern: LF-HRV reactivity was more positive in the reward-12-Swiss-Francs cell than in the reward-2-Swiss-Francs cell. I will discuss this finding in detail in the general discussion.

SBP, MAP, DBP, and IBI reactivity did not show the predicted interaction between reward value and task context. The results for MAP, DBP, and IBI are not surprising given that the research on Wright's integrative model (Wright, 1996) has not consistently found effects on these parameters (Gendolla & Wright, 2005; Gendolla, Brinkmann, & Richter, 2007; Richter et al., 2006; Wright, 1996; Wright & Kirby, 2001, for reviews). However, the result for SBP reactivity is in contrast to the preceding research. Most studies in the frame of motivational intensity theory found effects on SBP reactivity. Nevertheless, since SBP is a joint function of myocardial contractility and vascular resistance, myocardial beta-adrenergic effects on SBP might have been masked by parallel decreases in total peripheral resistance.

Experiment 2

According to Wright's (1996) integration of motivational intensity theory (Brehm & Self, 1989) and the active coping approach Obrist (1981), cardiovascular responses should be proportional to reward value if the performance standard is either fixed and unclear or unfixed. Experiment 1 provided first evidence that this "default" relationship between reward and cardiovascular responses can be overridden by context factors. However, the performance standard of the task employed in Experiment 1 was fixed—participants had to recall all of the presented letter series to earn the reward. Thus, it demonstrates only that task context may moderate the reward-cardiovascular response relationship when participants perform a task with a fixed but unclear performance standard. The second experiment aimed to replicate the findings of the first study and to generalize these findings by demonstrating that task context may also moderate the reward impact on cardiovascular response if performers are free to perform at any level (i.e., if the performance standard is unfixed).

Method

Participants and Design

Fifty-six first-year psychology students (mean age 22 years) were randomly assigned to the conditions of a 2 (task context: reward vs. demand) x 2 (reward value: 0.05 Swiss Francs vs. 0.25 Swiss Francs) between-persons design. The distributions of women and men were as follows: 13 women and 1 man in both the reward-0.05-Swiss-Francs cell and the demand-0.05-Swiss-Francs cell, 11 women and 3 men in the reward-0.25-Swiss-Francs cell, and 12 women and 2 men in the demand-0.25-Swiss-Francs cell.[3] The participation was anonymous and voluntary. Respondents participated for course credit. As in Experiment 1, I will only report the results of the sample restricted to female participants. The results for the complete sample including women and men were virtually identical.

Apparatus and Physiological Measures

The presentation of stimuli and instructions was controlled by E-Prime 2 (Psychology Software Tools, Pittsburgh, PA). The software also collected and saved participants' responses. The Vasotrac blood pressure monitor (Medwave, Arden Hills, MN) and the Cardioscreen 1000 system (medis, Ilmenau, Germany) assessed SBP, DBP, MAP, HR, ECG and ICG during baseline and task performance. Application of the blood pressure cuff and the electrodes was identical to Experiment 1. The experimenter was hired and ignorant of the hypotheses.

Scanning Task

In contrast to Experiment 1, participants performed a visual scanning task. Each trial of this task started with a fixation cross that lasted for 750 ms. The cross was followed by a 3 x 4 matrix consisting of 12 random letters printed in black. After 500 ms, a single target letter appeared above the matrix. Participants had to decide within the next 2000 ms if the target letter was an element of the letter matrix or not. If the target letter appeared in the matrix, they had to press a button. No response was required if the target letter was not included in the matrix. After the participant had pressed the button, a message informed her or him that the response had been collected. This message lasted for the rest of the 2000 ms. Between two consecutive trials a blank screen was presented for 500 ms. The task consisted of 96 trials.

Procedure

The experiment was run in individual sessions. Having applied the blood pressure cuff and the Cardioscreen electrodes, the experimenter started the computer software and left the room. After some biographical questions, the experimenter instructed the participants to sit as calmly as possible during the next 10 minutes. During this baseline period, cardiovascular measures were taken while the participants could leaf through some magazines. After baseline period, participants received the instructions for the visual scanning task. Furthermore, they were informed that they could earn some money by successfully performing the task. They learned that for each correct response—pressing the button when the target letter appeared in the letter matrix—they would earn a small amount of money. For each false response—pressing the button when the target letter was not included in the matrix—the same amount would be deducted. One half of the participants learned that they could earn 0.05 Swiss Francs (about USD 0.05) for each correct response, the other half were informed that they could earn 0.25 Swiss Francs (about USD 0.23) for each correct response.

After task instructions, participants answered five questions either related to task reward (reward context) or task demand (demand context). Eight of the ten questions were similar to the questions used in Experiment 1. In the reward context condition a question related to the expected total amount of reward ("How much money do you expect to earn overall?") replaced the question related to satisfaction. In the demand condition the question related to exhaustion was replaced by "How difficult will it be for you to react correctly and faster than 2 seconds?". In contrast to Experiment 1, participants made their ratings on visual analog scales ranging from *not at all* or *nothing at all*, respectively, to *very much*. Participants then performed the 96 task trials while cardiovascular measures were assessed. After task performance, participants rated the same question related to task difficulty as in Experiment 1 using a visual analog scale ranging from *very easy* to *very difficult*. Finally, participants were debriefed, probed for suspicion, and received their course credit and the monetary reward.

Data Scoring, Reduction, and Analysis

Data scoring and reduction followed the procedures described in Experiment 1. Again, PEP was rated by two independent raters, who showed a high agreement (ICC[2,1] = .81) (Shrout & Fleiss, 1979). Consequently, the arithmetic mean of both raters' PEP values was used for the analyses. As in Experiment 1, the arithmetic means of all measures collected during the last five minutes of habituation constituted our baseline scores (Cronbach's αs > .98) and the arithmetic means of all measures obtained during task performance were used as cardiovascular task scores (Cronbach's αs > .98). Cardiovascular reactivity scores were computed by subtracting baseline scores from task scores. Given that LF-HRV reactivity scores were significantly correlated with LF-HRV baseline scores ($r = -.30$, $p = .04$), we included LF-HRV baseline scores in all analyses involving LF-HRV reactivity. All other cardiovascular reactivity scores did not significantly correlate with their respective baseline scores ($-.14 < r$s $< .13$, ps $> .38$) and were, therefore, not corrected. Data analysis followed Experiment 1. All cardiovascular reactivity measures were first analyzed using a planned contrast that mimicked the predicted reactivity pattern (Contrast cell weights were -1 for the demand-0.05-Swiss-Francs cell, -1 for the demand-0.25-Swiss-Francs cell, -1 for the reward-0.05-Swiss-Francs cell, and +3 for the reward-0.25-Swiss-Francs cell). The main contrast was followed by two contrasts that examined the simple reward effects at each level of task context.

Results

Preliminary Analyses

Participants' BMI scores did not differ between the conditions (*p*s > .14). Cardiovascular baseline and reactivity scores were not significantly correlated with BMI scores (-.26 < *r*s < .23, *p*s > .09).

Cardiovascular Baselines

There were no significant effects on cardiovascular baselines (*p*s > .10) in 2 (task context) x (reward value) between-persons ANOVAs. Table 4 shows cell means and standard errors of cardiovascular baselines scores.

Cardiovascular Reactivity

PEP reactivity. The main contrast was significant, *F*(1, 45) = 5.92, *p* =.02, *MSE* = 49.88, = .12. The residual was not significant (*p* = .73). PEP reactivity was significantly stronger in the reward-0.25-Swiss-Francs cell (*M* = -7.77, *SE* = 3.25) than in the reward-0.05-Swiss-Francs cell (*M* = -1.23, *SE* = 1.35), *F* (1, 45) = 5.11, *p* =.03, = .10. The difference between the demand-0.05-Swiss-Francs cell (*M* = -1.94, *SE* = 1.69) and the demand-0.25-Swiss-Francs cell (*M* = -2.49, *SE* = 1.64) was not significant (*p* = .84). Figure 2 displays the pattern of PEP reactivity.

Blood pressure reactivity. The main contrast was not significant for SBP, DBP, or MAP reactivity (*p*s > .28). The only simple reward effect that approached significance was a slightly stronger SBP reactivity in the reward-0.25-Swiss-Francs cell than in the reward-0.05-Swiss-Francs cell, *F* (1, 42) = 3.10, *p* =.09, *MSE* = 47.17, = .07 (all other *p*s > .16). Table 5 displays cell means and standard errors of SBP, MAP, and DBP reactivity.

IBI reactivity. The main contrast was not significant (*p* = .14). However, analyses of the reward effects at each level of task context showed that IBI reactivity was stronger in the reward-

0.25-Swiss-Francs cell than in the reward-0.05-Swiss-Francs cell, $F(1, 44) = 5.35$, $p = .03$, $MSE = 2150.21$, = .11, and did not differ between both demand cells ($p = .55$). Cell means and standard errors of IBI reactivity appear in Table 5.

HRV reactivity. The planned contrast was not significant for RMSSD and HF-HRV reactivity (ps > .26). Unexpectedly, the reward analyses at each level of task context showed a significant difference between both demand context cells for RMSSD, $F(1, 44) = 4.26$, $p = .04$, $MSE = 0.03$, = .09, and for HF-HRV, $F(1, 44) = 5.88$, $p = .02$, $MSE = 0.14$, = .12. The differences between both reward context cells were not significant ($ps > .45$). The main contrast approached significance for LF-HRV reactivity, $F(1, 43) = 3.44$, $p = .07$, $MSE = 0.29$, = .07 (residual $p = .72$). There were no simple reward effects (ps > .15) on LF-HRV reactivity. Table 5 displays cell means and standard errors of HRV reactivity.

Task Performance

A 2 (task context) x 2 (reward value) between-persons ANOVA did not reveal any significant effects on the percentage of correct responses (ps > .19). Tukey’s HSD tests did not reveal any significant differences between the cells (ps > .31). The correlations between the percentage of correct responses and reactivity scores were not significant ($-.13 < r$s $< .18$, ps > .24). Cell means and standard errors of the percentage of correct responses were as follows: $M = 93.35$ and $SE = 0.68$ in the reward-0.05-Swiss-Francs cell, $M = 91.67$ and $SE = 1.13$ in the reward-0.25-Swiss-Francs cell, $M = 91.83$ and $SE = 1.37$ in the demand-0.05-Swiss-Francs cell, $M = 90.45$ and $SE = 1.37$ in the demand-0.25-Swiss-Francs cell.

Task Ratings

Pre-task ratings were compared within each task context condition using *t*-tests for independent samples.[4] These tests revealed that participants in the reward-0.25-Swiss-Francs cell rated the reward as more attractive and expected to earn a higher total monetary reward than participants in the reward-0.05-Swiss-Francs cell, ($t[22]$s > 2.71, ps < .02). All other pairwise comparisons were not significant (ps > .05). Table 6 shows the cell means and standard errors of all pre-task ratings.

A 2 (task context) x 2 (reward value) between-persons ANOVA of the post-task difficulty ratings showed no significant effects (*p*s > .05). Furthermore, Tukey's HSD tests revealed no significant differences between the cells (*p*s > .07). Cell means and standard errors of the post-task difficulty ratings were as follows: *M* = 109.23 and *SE* = 24.05 in the reward-0.05-Swiss-Francs cell, *M* = 112.27 and *SE* = 24.12 in the reward-0.25-Swiss-Francs cell, *M* = 121.15 and *SE* = 23.23 in the demand-0.05-Swiss-Francs cell, *M* = 196.83 and *SE* = 27.12 in the demand-0.25-Swiss-Francs cell.

Discussion

As in Experiment 1, PEP reactivity during task performance showed the predicted interaction between reward value and task context. If participants had rated the monetary reward, PEP reactivity was higher when participants could earn 0.25 Swiss Francs for each correct response than when they could earn only 0.05 Swiss Francs. If participants had rated task demand, PEP reactivity did not differ as a function of reward value. In contrast to Experiment 1, IBI reactivity also showed a statistically significant reward effect in the reward context condition. Again, there were no significant effects on SBP, DBP, or MAP reactivity.

As in Experiment 1, there were significant effects on HRV reactivity. LF-HRV tended to parallel the PEP reactivity pattern but the reward effect in the reward context condition was not statistically significant. As in Experiment 1, the effects on LF-HRV were inconsistent with the interpretation of decreases in LF-HRV as an indicator of mental effort: LF-HRV reactivity was more positive when participants engaged to earn the high reward. The effects on RMSSD and HF-HRV reactivity were unexpected. Both measures showed significantly higher reactivity in the demand-0.25-Swiss-Francs cell than in the demand-0.05 Swiss-Francs cell.

General Discussion

The observed PEP reactivity patterns support the predicted moderating impact of task context on the relationship between reward value and cardiovascular reactivity. If participants had rated aspects of the monetary reward that they could earn before performing the task, PEP reactivity increased with increasing reward value: PEP reactivity was high when participants could earn the high monetary reward and was low when they could earn the low reward. If participants had rated task demand before task performance, PEP reactivity did not differ as a function of reward value.

Since PEP reactivity reflects changes in the force of myocardial contraction, which is influenced by changes in beta-adrenergic activity on the heart, the observed pattern of PEP reactivity may reflect underlying differences in myocardial beta-adrenergic activity (e.g., Harris, Schoenfeld, & Weissler, 1967; Lewis, Rittogers, Forester, & Boudoulas, 1977; Sherwood et al., 1990). However, beta-adrenergically driven changes in the force of myocardial contraction are not the only determinants of PEP changes. Changes in cardiac preload (ventricular filling) or cardiac afterload (aortic diastolic pressure) may also alter PEP (e.g. Lewis, 1974). Increases in preload increase the force of myocardial contraction via the Frank-Starling mechanism. This leads to a decrease in PEP. Increases in afterload lengthen PEP as it takes longer to build up the necessary force to open the aortic valves. Because of these multiple influences on PEP, some authors suggested that changes in PEP should only be interpreted in the light of the changes of other cardiovascular parameters (Obrist et al., 1987; Sherwood et al., 1990). According to these authors, decreases in PEP reflect increases in myocardial beta-adrenergic activity if they are accompanied by stable or increased HR and DBP.

If changes in cardiac preload could explain the PEP reactivity data, one would expect that HR decreases with decreasing PEP (Obrist et al., 1987). The data show no evidence that this was the case. In Experiment 1, the high PEP reactivity in the reward-12-Swiss-Francs cell—reflecting a decline in PEP from baseline to task performance—was not accompanied by a positive IBI reactivity, which would indicate a reduction in HR from baseline to task performance. The same applies to Experiment 2. Thus, it is unlikely that our PEP reactivity patterns were due to changes in cardiac preload. Our DBP data—which can be used as a rough estimation of aortic diastolic pressure—do not suggest that changes in cardiac afterload explain our PEP reactivity patterns. If PEP changes were due to changes in afterload, high PEP reactivity values should have been accompanied by low (or even negative) DBP reactivity values, whereas low PEP reactivity values should have been accompanied by high DBP reactivity values. Again, our data show no evidence that this was the case. Thus, neither changes in cardiac preload nor changes in cardiac afterload offer a plausible explanation for the PEP reactivity patterns that I have found. Consequently, the observed PEP effects should be interpreted as reflecting underlying changes in myocardial beta-adrenergic activity.

By demonstrating that reward value has an impact on beta-adrenergic activity our studies add to the research that supports Wright's (1996) notion that the effects of task difficulty and success importance on cardiovascular responses are mediated by beta-adrenergic impact on the heart (Annis et al., 2001; Richter et al., 2008; Richter & Gendolla, 2009). However, in contrast to the major part of the preceding research that has been conducted in the frame of Wright's model, I did not find effects on blood pressure. Especially for SBP, this was an unexpected finding. Among SBP, MAP, DBP, and HR, SBP has the most reliably followed the predictions of motivational intensity theory (Gendolla & Wright, 2005; Gendolla et al., 2007; Richter et al., 2006; Wright, 1996; Wright & Kirby, 2001, for reviews). Interestingly, one of the few studies that have directly investigated the impact of task difficulty and success importance on myocardial beta-adrenergic activity, has also found a dissociation between PEP and SBP reactivity. In the study of Annis and colleagues (Annis et al., 2001), PEP reactivity showed the predicted impact of task difficulty and ability feedback but SBP and HR reactivity did not. Since blood pressure is a function of myocardial contractility and total peripheral resistance (TPR), effects of changes in the force of myocardial contraction on blood pressure may be counteracted by opposing effects on TPR. Correspondingly, the absence of effects on blood pressure reactivity might have been due to a masking of the increase in myocardial contractility by a decline in TPR.

The observed difference in PEP reactivity between the reward context-high reward cells and the reward context-low reward cells replicates the result of a previous study that has demonstrated a linear increase of beta-adrenergic activity with increasing reward value under conditions of an unclear performance standard (Richter & Gendolla, 2009). In line with this finding, I found that beta-adrenergic reactivity was higher when participants could earn a high monetary reward than when they could earn a low monetary reward. Our data extend this previous study by demonstrating that the association between reward value and beta-adrenergic response does not rely on the unclear performance standard. PEP reactivity was only a function of reward value if participants had answered questions about the monetary reward. If participants had responded to questions about task demand, reward value had no impact on PEP reactivity.

Thus, the data suggest that the relationship between reward and cardiovascular response is moderated by context factors, as for instance manipulation checks. The implications for research on the impact of reward on cardiovascular response are straightforward. The hypothesis of a linear relationship between reward and cardiovascular responses, as it was postulated in some models (e.g., Elliot, 1969; Fowles, 1983; Smith et al., 1989), does only hold if the reward that participants can earn is salient. Presenting too much additional information—as for instance the manipulation of other variables—may reduce the salience of the reward and thereby lead to a failure in replicating the association between reward and cardiovascular responses (e.g., Manuck & Garland, 1979). Future research that examines reward impact on cardiovascular responses should consider this finding and should make sure that reward is salient.

The present studies constitute the first studies in the frame of Wright's integrative model that have assessed measures of HRV. Unfortunately, I could not replicate the results of previous studies that have supported the use of HRV as indicator of mental effort (e.g., Mulder et al., 2007; Segerstrom & Solberg Nes, 2007). RMSSD and HF-HRV reactivity did not show the predicted pattern and were not associated with PEP reactivity, the main dependent variable in the present studies. In Experiment 2, these measures showed an unexpected reward effect when participants had rated task demand before performing the task. This effect did not appear in Experiment 1 and I am not aware of any theoretical or empirical reason why reward effects on RMSSD and HF-HRV should appear in a demand context but not in a reward context. LF-HRV tended to parallel the effects on PEP reactivity. However, in contrast to previous research (e.g., Mulder et al., 2007; Rowe, Silbert, & Irving, 1998), LF-HRV did not decrease during effortful task performance but increased. If participants had rated task reward before performing the task, LF-HRV reactivity was more positive when participants could earn the high reward than when they could earn the low reward. There are different possible explanations for this unexpected effect on LF-HRV reactivity. First, one of the factors determining LF-HRV is sympathetic nervous activity (e.g., Berntson et al., 1997; Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996). Increases in sympathetic activity associated with mental stress can thus lead to increases in LF-HRV. Given that our PEP reactivity pattern indicates an increase in myocardial sympathetic activity, the increase in LF-HRV during task performance may be due to increased sympathetic activity. Second, several different methods have been used to calculate HRV time domain measures. Even if there is evidence that different HRV measures are highly correlated (e.g., Kleiger et al., 1991), it cannot be ruled out that the problems in replicating previous HRV effects are due to the different methods employed to analyze HRV. It should also be noted that most authors that have proposed HRV measures as indicators of mental effort have focused on the effects of mental workload or task demand. Most studies have manipulated task demand and observed corresponding changes in HRV. It might be that HRV measures are sensitive to changes in workload or task demand but not to changes in resource investment in general.

It is of note that Experiment 2—in contrast to Experiment 1—included the possibility of “loosing” money. If participants did erroneously respond in a trial a fixed amount of money was deducted from the money that they had already earned. At first sight, this may seem to constitute a qualitative difference between both experiments: a reward manipulation in Experiment 1 versus a mixture of reward and punishment in Experiment 2. However, it should be noted that participants in Experiment 2 could not really loose money. If a participant had incorrectly responded in all trials, he would have gotten no money—which is exactly the same as for a participant in Experiment 1 who does not correctly recall the letter series. Thus, if not earning the maximum amount of money constitutes a punishment, earning no money at all also constitutes a punishment. Nevertheless, one may speculate that participants in Experiment 2 had the impression of being punished during task performance. However, participants did not receive feedback if their response in a certain trial was correct or incorrect. Consequently, participants could not know about their performance or the money that they had earned until the end of the task—as in Experiment 1. It seems thus unlikely that participants in Experiment 2 felt punished during task performance. Furthermore, from the point of view of Wright’s integrative model there is no fundamental difference between the opportunity of earning a reward by a successful performance and the opportunity of avoiding a punishment by a successful performance. Both increase success importance and—by this means—the maximally justified amount of resources.

The presented results raise some interesting questions about the determinants of resource mobilization. At first sight, the results seem to imply that individuals can either focus on task difficulty, forgetting task reward, or focus on task reward, forgetting task difficulty. This would strongly conflict with previous research that has repeatedly demonstrated that individuals consider both task difficulty and task reward when mobilizing resources (e.g., Gendolla & Richter, 2006, Wright et al.,1995). It would also conflict with motivational intensity theory's prediction that both task difficulty and success importance determine resource mobilization if the performance standard is fixed and known. However, there is an alternative interpretation of the data that fits with preceding research and motivational intensity theory. Motivational intensity theory highlights the importance of the resource conservation principle for resource mobilization. However, the motivation to avoid wasting resources is not sufficient to explain why individuals engage in behavior. Individuals engage in instrumental tasks because these tasks are instrumental, that is individuals can attain goals (e.g., earn a monetary reward) by successfully performing the task. Thus, resource investment or effort, respectively, seems to be governed by at least two motivations: the motivation to attain a personal goal and the motivation to avoid wasting resources. The results of the presented studies suggest that the motivation to avoid wasting resources is not always of major importance. If individuals strongly focus on the reward that they can earn, resource mobilization will be mainly governed by the motivation to earn the reward and not by resource conservation considerations. As a consequence, resource mobilization will be a function of reward value. The motivation to conserve resources will be strengthened when task demand is salient and, under this condition, resource mobilization will be a function of task demand as long as the necessary effort is justified by success importance. Thus, the presented results do not contradict previous research or motivational intensity theory but provide first evidence that there is no primacy of resource conservation. Nevertheless, it should be noted that the presented studies only constitute a first step by demonstrating that the impact of reward value on PEP reactivity depends on the task context. Future research has to show that the focus on task reward can override task difficulty information in designs that involve the manipulation of task difficulty over at least two levels. The demonstration that resource mobilization is directly determined by task reward and independent of the objective level of task demand if individuals focus on task reward would provide strong evidence for the task context hypothesis. Future research should also use a more balanced sample including an equal number of male and female participants to enable a generalization to both female and male participants.

In sum, the presented data support the prediction that reward impact on cardiovascular (beta-adrenergic) reactivity is moderated by the task context. If participants focus on the monetary reward that they can earn by successfully performing a task, cardiovascular reactivity rises with reward value. If task demand is salient, cardiovascular reactivity is not directly influenced by reward value. Thereby, our studies suggest that it is crucial to pay attention to the whole task context—including task instructions and manipulation checks—when studying the effects of reward on cardiovascular responses.

References

Annis, S., Wright, R. A., & Williams, B. J. (2001). Interactional influence of ability perception and task demand on cardiovascular response: appetitive effects at three levels of challenge. *Journal of Applied Biobehavioral Research, 6*, 82–107.

Belanger, D., & Feldman, S. M. (1962). Effects of water deprivation upon heart rate and instrumental activity in the rat. *Journal of Comparative and Physiological Psychology, 55*, 220–225.

Benjamin, L. (1967). Facts and artifacts in using analysis of covariance to ”undo” the law of initial values. *Psychophysiology, 4*, 187–206.

Berne, R. M., & Levy, M. N. (1977). *Cardiovascular physiology.* St. Louis: C. V. Mosby.

Berntson, G. G., Bigger, T., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., Nagaraja, H. N., Porges, S. W., Saul, J. P., Stone, P. H., & van der Molen, M. W. (1997). Heart rate variability: Origins, methods, and interpretative caveats. *Psychophysiology, 34*, 623-648.

Berntson, G. G., Lozano, D. L., Chen, Y.-J., & Cacioppo, J. T. (2004). Where to Q in PEP. *Psychophysiology, 41*, 333–337.

Brehm, J. W., & Self, E. A. (1989). The intensity of motivation. *Annual Review of Psychology, 40*, 109–131.

Brenner, S. L., Beauchaine, T. P., & Sylvers, P. D. (2005). A comparison of psychophysiological and self-report measures of BAS and BIS activation. *Psychophysiology, 42*, 108–115.

Elliot, R. (1969). Tonic heart rate: Experiment on the effects of collative variables lead to a hypothesis about its motivational significance. *Journal of Personality and Social Psychology, 12*, 211–228.

Eubanks, L., Wright, R. A., & Williams, B. J. (2002). Reward influence on the heart: cardiovascular response as a function of incentive value at five levels of task demand. *Motivation and Emotion, 26*, 139–152.

Fowles, D. C. (1983). Appetitive motivational influences on heart rate. *Personality and Individual Differences, 4*, 393–401.

Fowles, D. C., Fisher, A. E., & Tranel, D. T. (1982). The heart beats to reward: The effect of monetary incentive on heart rate. *Psychophysiology, 19*, 506–513.

Furr, R. M., & Rosenthal, R. (2003). Evaluating theories efficiently: The nuts and bolts of contrast analysis. *Understanding Statistics, 2*, 45–67.

Ganong, W. F. (2005). *Review of medical physiology.* New York: McGraw- Hill.

Gendolla, G. H. E., Brinkmann, K., & Richter, M. (2007). Mood, motivation, and performance: An integrative theory, research, and applications. In A. M. Lane (Ed.), *Mood and human performance: Conceptual, measurement, and applied issues* (pp. 35-61). Hauppauge, NY: Nova Science.

Gendolla, G. H. E., & Richter, M. (2006). Ego-involvement and the difficulty law of motivation: effects on performance-related cardiovascular response. *Personality and Social Psychology Bulletin, 32*, 1188–1203.

Gendolla, G. H. E., & Wright, R. A. (2005). Motivation in social settings: studies of effort-related cardiovascular arousal. In J. P. Forgas, K. Williams, & W. von Hippel (Eds.), *Social motivation* (pp. 71-90). New York: Cambridge University Press.

Harris, W. S., Schoenfeld, C. D., & Weissler, A. M. (1967). Effects of adrenergic receptor activation and blockade on the systolic preejection period, heart rate, and arterial pressure in man. *The Journal of Clinical Investigation, 46*, 1704–1714.

Kelsey, R. M., & Guethlein, W. (1990). An evaluation of the ensemble averaged impedance cardiogram. *Psychophysiology, 27*, 24–33.

Kleiger, R. E., Bigger, J. T., Bosner, M. S., Chung, M. J., Cook, J. R., Rolnitzky, L. M., Steinman, R., & Fleiss, J. L. (1991). Stability over time of variables measuring heart rate variability in normal subjects. *The American Journal of Cardiology, 68*, 626-630.

Lewis, R. P. (1974). Systolic time intervals. In A. M. Weissler (Ed.), *Noninvasive cardiology* (pp. 301–368). New York: Grune & Stratton.

Lewis, R. P., Rittogers, S. E., Forester, W. F., & Boudoulas, H. (1977). A critical review of the systolic time intervals. *Circulation, 56*, 146–158.

Light, K. C., & Obrist, P. A. (1980). Cardiovascular response to stress: effects of opportunity to avoid, shock experience, and performance feedback. *Psychophysiology, 17*, 243–252.

Lippman, N., Stein, K. M., & Lerman, B. B. (1994). Comparison of methods for removal of ectopy in measurement of heart rate variability. *AJP – Heart and Circulatory Physiology, 267*, 411-418.

Lipsitt, L. P., Reilly, B. M., Butcher, M. J., & Greenwood, M. M. (1976). The stability and interrelationships of newborn sucking and heart rate. *Developmental Psychobiology, 9*, 305–310.

Llabre, M. M., Spitzer, S. B., Saab, P. G., Ironson, G. H., & Schneiderman, N. (1991). The reliability and specificity of delta versus residualized change as measures of cardiovascular reactivity to behavioral challenges. *Psychophysiology, 28*, 701–711.

Manuck, S. B., & Garland, F. N. (1979). Coronary-prone behavior pattern, task incentive, and cardiovascular response. *Psychophysiology, 16*, 136–142.

Mulder, B., Rusthoven, H., Kuperus, M., de Rivecourt, M., & de Waard, D. (2007). Short-term heart rate measures as indices of momentary changes in invested mental effort. In D. de Waard, G. R. J. Hockey, P. Nickel, & K. A. Brookhuis (Eds.), *Human factors issues in complex system performance* (pp. 101-116). Maastricht: Shaker Publishing.

Obrist, P. A. (1976). The cardiovascular-behavioral interaction as it appears today. *Psychophysiology, 13*, 95–107.

Obrist, P. A. (1981). *Cardiovascular psychophysiology: A perspective*. New York: Plenum.

Obrist, P. A., Gaebelein, C. J., Teller, E. S., Langer, A. W., Grignolo, A., Light, K. C., & McCubbin, J. A. (1978). The relationship among heart rate, carotid dP/dt, and blood pressure in humans as a function of the type of stress. *Psychophysiology 15 (2)*, 102–115.

Obrist, P. A., Light, K. C., James, S. A., & Strogatz, D. S. (1987). Cardiovascular responses to stress: I. Measures of myocardial response and relationships to high resting systolic pressure and parental hypertension. *Psychophysiology, 24*, 65–78.

Richter, M., Friedrich, A., & Gendolla, G. H. E. (2008). Task difficulty effects on cardiac activity. *Psychophysiology, 45*, 869–875.

Richter, M., & Gendolla, G. H. E. (2006). Incentive effects on cardiovascular re- activity in active coping with unclear task difficulty. International Journal of *Psychophysiology, 61*, 216–225.

Richter, M., & Gendolla, G. H. E. (2007). Incentive value, unclear task difficulty, and cardiovascular reactivity in active coping. *International Journal of Psychophysiology, 63*, 185–192.

Richter, M., & Gendolla, G. H. E. (2009). The heart contracts to reward: monetary incentives and pre-ejection period. *Psychophysiology, 46*, 451–457.

Richter, M., Gendolla, G. H. E., & Krüsken, J. (2006). Context-dependent mood effects on mental effort mobilization: A view from the Mood-Behavior- Model. In A. V. Clark (Ed.), *The psychology of moods* (pp. 57–79). Hauppauge, NY: Nova Science Publishers.

Rosenthal, R., & Rosnow, R. L. (1985). *Contrast analysis*. New York: Cambridge University Press.

Rowe, D. W., Silbert, J., & Irwin, D. (1998). Heart rate variability: Indicator of user state as an aid to human-computer interaction. In *Proceedings of Conference on Human Factors in Computing Systems (CHI '98)*, 480-487.

Scherhag, A. W., Kaden, J. J., Kentschke, E., Sueselbeck, T., & Borggrefe, M. (2005). Comparison of impedance cardiography and thermodilution-derived measurements of stroke volume and cardiac output at rest and during exercise testing. *Cardiovascular Drugs and Therapy, 19*, 141–147.

Segerstrom, S. C., & Solberg Nes, L. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological Science, 18*, 275-281.

Sherwood, A., Allen, M. T., Fahrenberg, J., Kelsey, R. M., Lovallo, W. R., & van Doornen, L. P. J. (1990). Methodological guidelines for impedance cardiography. *Psychophysiology, 27*, 1–23.

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: uses in assessing rater reliability. *Psychological Bulletin, 86*, 420–428.

Smith, T. W., Allred, K. D., Morrison, C. A., & Carlson, S. D. (1989). Cardiovascular reactivity and interpersonal influence: active coping in a social context. *Journal of Personality and Social Psychology, 56*, 209–218.

Smith, T. W., Nealey, J. B., Kircher, J. C., & Limon, J. P. (1997). Social determinants of cardiovascular reactivity: Effects of incentive to exert influence and evaluative threat. *Psychophysiology, 34*, 65–73.

Smith, T. W., Ruiz, J. M., & Uchino, B. N. (2000). Vigilance, active coping, and cardiovascular reactivity during social interaction in young men. *Health Psychology, 19*, 382–392.

Tarvainen, M. P., Ranta-aho, P. O., & Karjalainen, P. A. (2001). An advanced detrending method with application to HRV analysis. *IEEE Transactions in Biomedical Engineering, 49*, 1272-175.

Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996). Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *Circulation, 93*, 1043-1065.

Tranel, D. T. (1983). The effects of monetary incentive and frustrative non-reward on heart rate and electrodermal activity. *Psychophysiology, 20*, 652–657.

Tranel, D. T., Fisher, A. E.,& Fowles, D. C. (1982). Magnitude of incentive effects on heart rate. *Psychophysiology, 19*, 514–519.

Vicente, K. J., Thornton, D. C., & Moray, N. (1987). Spectral analysis of sinus arrhythmia: A measure of mental effort. *Human Factors, 29*, 171-182.

Wright, R. A. (1996). Brehm's theory of motivation as a model of effort and cardiovascular response. In P. M. Gollwitzer & J. A. Bargh (Eds.), *The psychology of action* (pp. 424–453). New York: Guilford.

Wright, R. A., Dill, J. C., Russell, G. G., & Anderson, C. A. (1998). Social evaluation influence on cardiovascular response to a fixed behavioral challenge: effects across a range of difficulty levels. *Annals of Behavioral Medicine, 20*, 277–285.

Wright, R. A., Killebrew, K., & Pimpalapure, D. (2002). Cardiovascular incentive effects where a challenge is unfixed: Demonstrations involving social evaluation, evaluator status, and monetary reward. *Psychophysiology, 39*, 188–197.

Wright, R. A., & Kirby, L. D. (2001). Effort determination of cardiovascular response: An integrative analysis with applications in social psychology. In P. M. Zanna (Ed.), *Advances in experimental social psychology* (vol. 33, pp. 255-307). San Diego, CA: Academic Press.

Wright, R. A., Tunstall, A. M., Williams, B. J., Goodwin, J. S., & Harmon- Jones, E. (1995). Social evaluation and cardiovascular response: an active coping approach. *Journal of Personality and Social Psychology, 69*, 530–543.

Footnotes

[1] In the literature on motivational intensity theory, the terms “fixed difficulty”, “unclear difficulty”, and “unfixed difficulty” are used to refer to the three kinds of tasks. “Fixed difficulty” refers to tasks where the performance standard is fixed and where individuals know about the level of this standard. “Unclear difficulty” refers to tasks where the performance standard is fixed but individuals do not know about the exact level of this standard. In both kinds of tasks, task outcome is dichotomous: If an individual attains or exceeds the required performance standard, the task counts as success. If an individual falls short of the required standard, the task counts as failure. “Unfixed difficulty” refers to tasks where no performance standard is fixed in advance and individuals are free to choose their own level of performance. As a consequence of this, there is no success-failure dichotomy in tasks with “unfixed difficulty”.

[2] Higher (i.e., more negative) PEP reactivity values indicate higher beta-adrenergic reactivity.

[3] Due to equipment failure the Vasotrac data of three participants in the reward-0.25-Swiss-Francs cell were lost. Correspondingly, statistical analyses involving blood pressure are only based on 53 participants.

[4] All visual analog scales were 500 pixels long and task ratings could, therefore, range between 1 and 500.

Author Note

This research was supported by a research grant (100014_118220) from the Swiss National Science Foundation. I am grateful to Kerstin Brinkmann and Guido Gendolla for comments on an early version of this paper. Correspondence should be addressed to Michael Richter, University of Geneva, FPSE, Dept. of Psychology, 40, Bd. du Pont-d'Arve, CH-1211 Geneva 4, Switzerland. Electronic mail can be sent to Michael.Richter@unige.ch.

Table 1

Cell Means and Standard Errors of Cardiovascular Baseline Scores in Experiment 1.

	Mean			Standard Error	
	2 CHF	12 CHF		2 CHF	12 CHF
			SBP		
reward context	112.84	118.34		3.94	3.74
demand context	118.05	113.04		3.33	3.64
			MAP		
reward context	81.19	85.53		3.09	3.33
demand context	85.14	81.65		2.60	2.88
			DBP		
reward context	63.76	66.66		2.49	2.71
demand context	65.81	64.20		2.20	2.42
			IBI		
reward context	795.55	791.65		29.32	32.44
demand context	818.57	799.39		25.69	31.13
			PEP		
reward context	102.28	111.19		3.13	3.48
demand context	110.46	109.58		4.17	3.92
			RMSSD		
reward context	3.65	3.54		0.13	0.14
demand context	3.69	3.59		0.12	0.21
			LF-HRV		
reward context	6.58	6.25		0.24	0.21
demand context	6.49	6.64		0.29	0.29
			HF-HRV		
reward context	6.17	5.97		0.28	0.28
demand context	6.46	6.19		0.26	0.46

CHF = Swiss Francs. SBP, MAP, and DBP are in millimeters of mercury. HR, PEP, and RMSSD are in milliseconds. LF-HRV and HF-HRV are in milliseconds squared.

Table 2

Cell Means and Standard Errors of Cardiovascular Reactivity Scores in Experiment 1.

	Mean		Standard Error	
	2 CHF	12 CHF	2 CHF	12 CHF
		SBP		
reward context	6.47	5.81	1.68	2.87
demand context	8.68	7.65	2.51	3.94
		MAP		
reward context	5.01	4.77	1.36	2.56
demand context	6.69	6.07	1.87	3.32
		DBP		
reward context	4.12	3.04	1.14	1.94
demand context	5.61	5.42	1.74	3.04
		IBI		
reward context	-53.32	-60.64	12.18	22.55
demand context	-63.25	-70.62	14.36	11.40
		RMSSD		
reward context	-0.05	0.02	0.04	0.08
demand context	-0.14	-0.22	0.09	0.08
		LF-HRV		
reward context	-0.29	0.33	0.17	0.19
demand context	-0.13	-0.34	0.16	0.18
		HF-HRV		
reward context	-0.05	0.17	0.16	0.18
demand context	-0.30	-0.35	0.16	0.17

CHF = Swiss Francs. SBP, MAP, and DBP are in millimeters of mercury. HR, PEP, and RMSSD are in milliseconds. LF-HRV and HF-HRV are in milliseconds squared.

Table 3

Cell Means and Standard Errors of Pre-task Ratings in Experiment 1.

	Mean		Standard Error	
	2 CHF	12 CHF	2 CHF	12 CHF
	Reward context condition			
Satisfaction	4.08	4.80	0.68	0.74
Importance of success	6.33	5.40	0.45	0.62
Reward value	2.00	4.50	0.25	0.73
Importance of winning	3.75	3.70	0.73	0.65
Attractiveness	1.92	5.00	0.36	0.56
	Demand context condition			
Effort	7.00	6.83	0.41	0.44
Ability	5.69	6.25	0.61	0.39
Exhaust	5.77	6.08	0.50	0.48
Probability	5.15	5.92	0.67	0.45
Difficulty	5.62	5.92	0.60	0.50

CHF = Swiss Francs.

Table 4

Cell Means and Standard Errors of Cardiovascular Baseline Scores in Experiment 2.

	Mean		Standard Error	
	0.05 CHF	0.25 CHF	0.05 CHF	0.25 CHF
SBP				
reward context	112.43	116.28	2.96	3.70
demand context	112.12	119.99	3.56	5.16
MAP				
reward context	80.21	82.80	2.24	2.93
demand context	80.36	87.12	3.02	4.24
DBP				
reward context	61.73	64.74	1.59	2.13
demand context	62.46	67.71	2.47	3.11
IBI				
reward context	796.96	815.28	31.30	38.83
demand context	812.11	815.96	29.66	33.89
PEP				
reward context	108.17	102.47	1.72	4.40
demand context	105.95	102.68	2.28	4.73
RMSSD				
reward context	3.68	3.66	0.13	0.17
demand context	3.76	3.53	0.11	0.12
LF-HRV				
reward context	6.82	6.48	0.18	0.26
demand context	6.37	6.20	0.35	0.24
HF-HRV				
reward context	6.49	6.19	0.25	0.33
demand context	6.36	5.99	0.22	0.21

CHF = Swiss Francs. SBP, MAP, and DBP are in millimeters of mercury. HR, PEP, and RMSSD are in milliseconds. LF-HRV and HF-HRV are in milliseconds squared.

Table 5

Cell Means and Standard Errors of Cardiovascular Reactivity Scores in Experiment 2.

	Mean		Standard Error	
	0.05 CHF	0.25 CHF	0.05 CHF	0.25 CHF
SBP				
reward context	3.23	8.66	1.55	3.62
demand context	6.02	8.14	1.79	1.69
MAP				
reward context	2.58	6.06	1.29	2.52
demand context	4.91	6.45	1.51	1.53
DBP				
reward context	2.08	4.30	0.92	1.84
demand context	3.61	4.46	1.25	1.32
IBI				
reward context	-10.01	-54.78	11.65	15.77
demand context	-47.69	-36.61	13.89	12.07
RMSSD				
reward context	-0.01	-0.02	0.06	0.06
demand context	-0.16	-0.02	0.04	0.05
LF-HRV				
reward context	-0.32	0.01	0.16	0.16
demand context	-0.42	-0.26	0.15	0.16
HF-HRV				
reward context	0.11	0.23	0.10	0.11
demand context	-0.11	0.25	0.08	0.14

CHF = Swiss Francs. SBP, MAP, and DBP are in millimeters of mercury. HR, PEP, and RMSSD are in milliseconds. LF-HRV and HF-HRV are in milliseconds squared.

Table 6

Cell Means and Standard Errors of Pre-task Ratings in Experiment 2.

	Mean		Standard Error	
	0.05 CHF	0.25 CHF	0.05 CHF	0.25 CHF
	Reward context condition			
Importance of winning	195.62	229.91	38.63	33.20
Importance of success	285.46	331.18	20.88	21.05
Attractiveness	147.69	272.45	24.42	40.88
Reward value	173.69	226.91	24.41	32.49
Total reward	140.54	246.91	23.47	26.44
	Demand context condition			
Effort	337.23	303.92	19.01	23.18
Ability	343.77	278.08	17.92	28.08
Difficulty of success	215.69	267.75	27.65	26.10
Probability	289.92	254.17	29.83	19.75
Difficulty of correct response	289.77	300.50	33.76	22.95

CHF = Swiss Francs. Range of ratings is from 1 to 500.

Figure Captions

Figure 1. Cell means and standard errors of pre-ejection period (PEP) reactivity in Experiment 1. ms = milliseconds.

Figure 2. Cell means and standard errors of pre-ejection period (PEP) reactivity in Experiment 2. ms = milliseconds.